Exoplanet Transit Database. Reduction and processing of the photometric data of exoplanet transits.

Stanislav Poddaný [a,b] Luboš Brát [c,d] Ondřej Pejcha [c,e]

[a] *Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, CZ-180 00 Prague 8, V Holešovičkách 2, Czech Republic*

[b] *Štefánik observatory, CZ-118 46 Prague 1, Petřín 205, Czech Republic*

[c] *Variable Star and Exoplanet Section of Czech Astronomical Society*

[d] *Altan observatory, CZ-542 21 Pec pod Sněžkou 193, Czech Republic*

[e] *Department of Astronomy, Ohio State University, Columbus, OH 43210, USA*

Abstract

We demonstrate the newly developed resource for exoplanet researchers - The Exoplanet Transit Database. This database is designed to be a web application and it is open for any exoplanet observer. It came on-line in September 2008. The ETD consists of three individual sections. One serves for predictions of the transits, the second one for processing and uploading new data from the observers. We use a simple analytical model of the transit to calculate the central time of transit, its duration and the depth of the transit. These values are then plotted into the observed - computed diagrams (O-C), that represent the last part of the application.

Key words: exoplanets, planetary systems, techniques: photometric, database
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1 Introduction

Research on extrasolar planets is currently one of the most exciting fields in astrophysics. The speculations on the existence of planets orbiting other solar-type stars ended fourteen years ago. In 1995 the discovery of the first extrasolar planet orbiting a solartype star - the well-known 51 Peg b, was

Email address: poddany@observatory.cz (Stanislav Poddaný).

made by Mayor & Queloz (1995). Since then, the number of known planets has been growing quickly. Currently, more than 370 such bodies are known[1].

If a planetary system happens to be oriented in the space so that the orbital plane is close to the line-of-sight to the observer, a planet periodically passes in front of the stellar disk. Photometric observation of the transit can then be used to derive the orbital and physical parameters of the planet (e.g., Southworth 2008 or Torres et al. 2008). For a review of properties that have been measured, or that might be measured in the future through precise observations of transiting planets see Winn (2008). At the half of the year 2009, more than 60 planets with this special orientation were known.

There are many amateur astronomers all over the world that achieved photometric accuracy around the units of percent, which is necessary for quality observing of the exoplanet transit. Unfortunately, up to present day, no exoplanet light curves' database was available that would accept data from both professionals as well as from amateurs. Amateur observers are not constrain by telescope scheduling and often have unlimited access to their instrument which enables them to gather data over a long period.

Huge quantity of observations is the key to the search for other planets in already known systems. It is important to monitor possible periodical changes in O-C plots of the planets because as Holman & Murray (2005) demonstrated in their theoretical work, short-term changes of the time of the transit can be caused by the presence of other exoplanets or moons in the system, see also Agol et al. (2005), Kipping (2009). On the other hand, potential long-term changes in the duration of the transit may be the consequence of orbital precession of exoplanets as Miralda-Escudé (2002) showed in his theoretical work. To perform such effective studies, we need a database which includes all available data divided into groups according their quality.

2 Why ETD

The Exoplanet Transit Database[2] (ETD) came on-line in September 2008 as a project of the Variable Star and Exoplanet Section of the Czech Astronomical Society. The ETD includes all known transiting planets that have published ephemerides.

[1] see the list http://www.exoplanet.eu
[2] http://var2.astro.cz/ETD

We have created on-line ETD portal to supply observers with such useful information like transit predictions, transit timing variation (TTV), variation of depth and duration with availability to draw user observation to the plot.

Before the ETD, only two other transit databases were available. The Amateur Exoplanet Archive[3] (AXA), lead by Bruce Gary, and the NASA/IPAC/NExScI Star and Exoplanet Database[4] (NStED) (von Braun et al. 2008). AXA strictly accepts data only from amateurs. Unfortunately, the quality of light curves is very diverse. In spite of this fact, all of the available light curves have the same priority grading. On the other hand NStED contains only the light curves that have been already published (in the future some amateur light curves from AXA should be also accepted into the NStED and the AXA should expire).

The main goal of the ETD is to gather all available light curves from professional and also amateur astronomers (after one year of the existence of the database, more than one thousand such records are available). We are searching for new publications on several open archives to gather all available light curves. We also take over data from the NStED, AXA and from our project TRESCA[5]. It is also possible to upload data into the database directly using a web-form or it can be added to the database by the administrators. All available data are on-line plotted into graphs where we make the provision for the quality of the light curve. All graphs (like TTV) can be easily downloaded from the database. It is also possible to download light curves from the TRESCA observers and from amateur observers directly from the database.

While collecting published data to ETD, we accentuate to have fully referenced its source. Each transit observation we store full reference with URL pointing to the paper or web-page where data were found. When we take over the whole light curve we display it only with reference to source of the data there is no mention of ETD in the picture.

3 Parts of the ETD

The ETD is composed from three sections. The first one - Transit prediction - serves for prediction of the transits. The second one - Model fit your data - is a web-form for accepting and processing new data. The last section - O-C plots - contains the observed - computed diagrams of the central times of transits, depths and the transit durations that are generated on-line from the database.

[3] http://brucegary.net/AXA/x.htm
[4] http://nsted.ipac.caltech.edu
[5] http://var2.astro.cz/EN/tresca

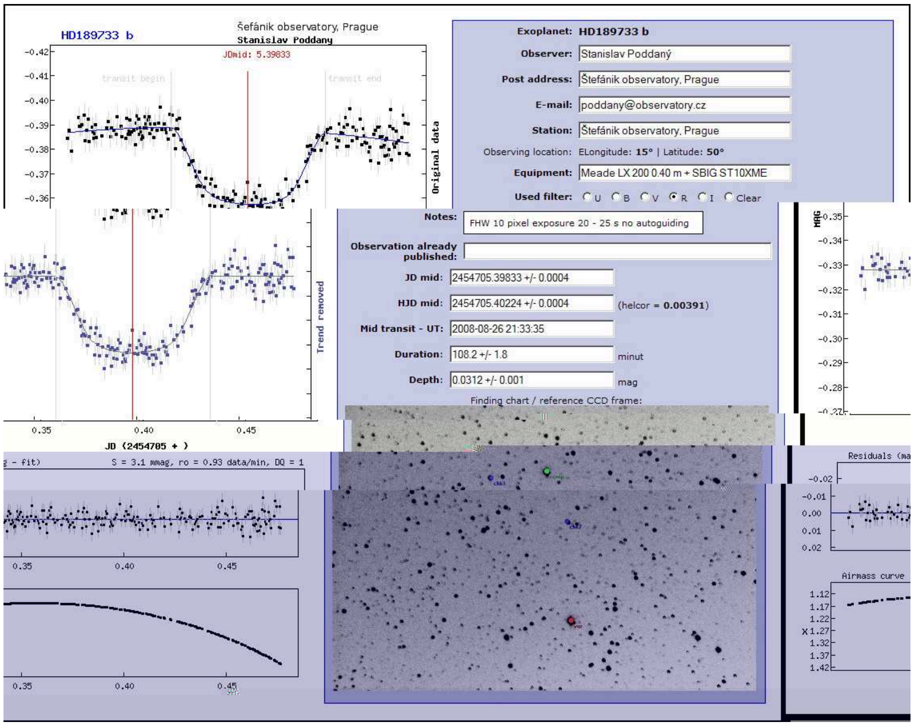

Fig. 1. A record sample in the ETD after successful processing the light curve.

3.1 Transit prediction

This section of the ETD contains one month prediction of observable transits (the starting day is the date two days before current date) and also the prediction for the next 365 days for selected exoplanet. Any observer can find here the time of the transit start/center/end, duration and the depth of each transit for any place in the world. Furthermore the altitude and the cardinal point of the object in the sky are displayed for the first contact, mid-transit time and the last contact. In the one year prediction window you can also see the finding chart[6] ($15'$ x $15'$).

3.2 Model-fit your data

This section describes an user-friendly web-form for uploading and processing the light curves into the database. To model-fit the transit we assume that the observations consist of N relative magnitudes m_i taken at times t_i ($i = 1, 2..., N$) and the photometry software provided measurement errors σ_i computed most likely from Poisson statistics and read-out noise. We model

[6] downloaded from the http://archive.stsci.edu/dss/index.html

the dataset by a function

$$m(t_i) = A - 2.5 \log F \left(z \left[t_i, t_0, D, b\right], p, c_1\right) + B(t_i - t_{\mathrm{mean}}) + C(t_i - t_{\mathrm{mean}})^2, \tag{1}$$

where $F(z, p, c_1)$ is a relative flux from the star due to the transiting planet. We assume that the planet and the star are dark and limb darkened disks, respectively, with radius ratio $p = R_P/R_*$ and that the planet is much smaller than the star, $p \lesssim 0.2$. The projected relative separation of the planet from the star is z. Limb darkening of the star is modeled by the linear law with the coefficient c_1. We employ the occultsmall routine of Mandel & Agol (2002) as our $F(z, p, c_1)$. We checked that the small planet approximation, $p \lesssim 0.2$, does not produce significant differences from the full model (at least for the typical values of p and having in the mind the typical quality of the photometry) and is much faster to compute, which is the most important factor for on-line processing.

We model the planet trajectory as a straight line over the stellar disk with impact parameter $b = a \cos I/R_*$, where a is a semi-major axis and I is the orbit inclination. The mid-transit occurs at t_0 and the whole transit lasts D. Based on these assumptions we can compute $z[t_i, t_0, D, b]$ for every t_i.

Variable A in the equation (1) descibes the zero-point shift of the magnitudes, while B and C describe systematic trends in the data. Linear and quadratic terms are computed with respect to the mean time of observations $t_{\mathrm{mean}} = \sum t_i/N$ to suppress numeric errors. We do not employ any explicit correction for air-mass curvature as we think a generic second-degree polynomial is sufficient in most cases.

We used the Levenberg-Marquardt non-linear least squares fitting algorithm from Press et al. (1992), procedure mrqmin. The algorithm requires initial values of parameters and partial derivatives of the fitted function. We take the initial values from literature (except for c_1, see below). We compute all partial derivatives of the equation (1) analytically, except for $\partial F/\partial z$, $\partial F/\partial p$ and $\partial F/\partial c_1$ which were computed numerically using Ridders' method (procedure dfridr of Press et al. 1992).

The search for the optimal parameters is done by iterating the fitting procedure until the $\Delta\chi^2$ (between fits) does not change significantly. Usually, with good initial values, about ten iterations are sufficient. Then the error bars σ_i are re-scaled to make the final $\chi^2 = N - g$, where g is a number of free parameters, and we re-run the fitting procedure to obtain final errors of the parameters. Original photometric errors are usually underestimated and this procedure yields more reasonable errors of the output parameters.

Table 1
The comparison of our results with Winn et al. (2007).

HD189733b	ETD	Winn et al. (2007)
central time [HJD]	2453988.80333 (12)	24543988.80331 (27)
duration [min.]	106.01 ± 0.50	109.62 ± 1.74

In the optimal circumstances, one would consider all variables in equation (1), namely A, B, C, t_0, D, b, p and c_1 free parameters. However, these parameters are correlated to some extent and noisy photometry from a small amateur telescopes does not permit recovery of all of them. We need to fit the zero-point shift A and in most cases also a linear systematic trend B. Our primary goal is to get the central time of the transit t_0, duration D and depth of the transit δ. Hence, we set t_0 and D as free parameters, by default. However, for a limb-darkened star, the depth of the transit δ is determined by radius ratio p, impact factor b and limb darkening coefficient c_1. Primarily, the depth of transit δ is governed by the radius ratio p and we set it as a free parameter. The parameters b and c_1 affect the depth and the shape of the transit to a lesser extent and from noisy amateur data we couldn't retrieve meaningful values for the two parameters simultaneously with p. Therefore, we hold b and c_1 fixed. We either compute b from orbital parameters of the planet and from the radius of the star or take the value from the literature. The situation is more complicated for limb darkening because c_1 should be different for every photometric filter. We decided to keep c_1 fixed at a rather arbitrary value $c_1 = 0.5$ in all cases. We experimented with values from 0.2 to 0.9 and found that the effect on other parameters is rather negligible, usually smaller than the error bars. The export value of the depth is then evaluated as

$$\delta = -2.5 \log \left[\min_z F \left(z, p, c_1 \right) \right]. \tag{2}$$

At Fig. 1 you can see the example of the record in the ETD after successful processing of the light curve.

We tested our algorithm using the data of the exoplanet HD189733b that were published by Winn et al. (2007). When we fitted this precise data using our code we obtained the value of the mid-transit time which was in excellent agreement with the published results. The duration of the transit wasn't inside the error bars. The errors of our fit are lower than those in the paper where the MCMC simulations were used (Tab. 1). We think that this excess is due to red noise which we did not take into account in our calculation and because of impact parameter that is fixed in our case. We also made a test with the data from AXA and we obtained similar results to the results presented in their archive (Tab. 2).

Table 2
The comparison of our results with the AXA database.

HD189733b	ETD	AXA
central time [HJD]	2454705.40228 (41)	2454705.4023 (5)
duration [min.]	102.09 ± 1.60	98.4 ± 1.8
depth [mag.]	0.0287 ± 0.0006	0.02895 ± 0.00080

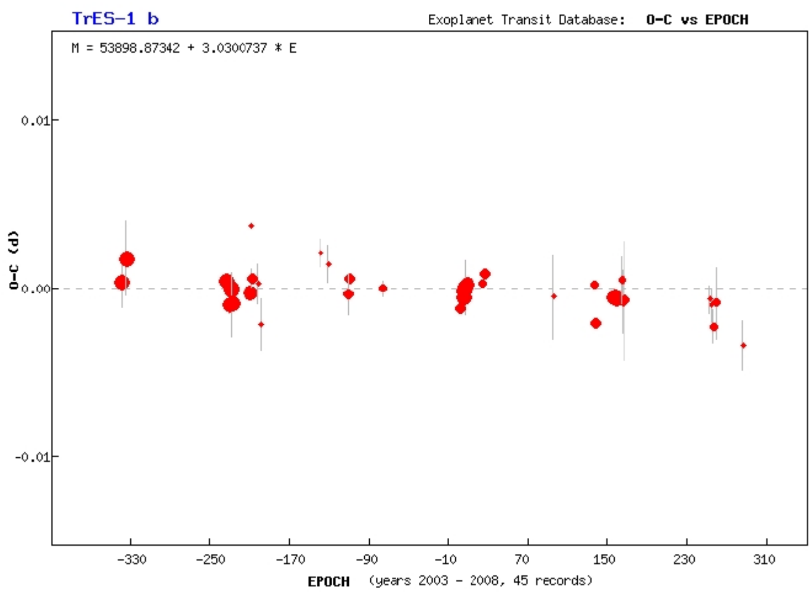

Fig. 2. The central transit time O-C plot for the exoplanet TrES-1 b in the ETD.

3.3 O-C plots

The O-C plots section contains the diagrams of the central transit time, the duration of the transit and its depth as a function of time. All available data for the selected planet including the error bars are visible in these graphs (Fig. 2). The quality of individual light curve is indicated by the size of the dot. The records in the ETD are divided into 5 groups according to their data quality index DQ. While computing DQ index of the light curve, the following relation is used

$$\alpha = \frac{\delta}{S}\sqrt{\rho} \qquad (3)$$

where α is a temporary data quality index, S is the mean absolute deviation of the data from our fit and $\rho = N/l$ means the data sampling, where l is the length of observing run in minutes.

Table 3
The distribution of the quality of the light curves according to their DQ index (example of the light curves see Figure 3).

DQ index	1	2	3	4	5
threshold	$\alpha \geq 9.5$	$9.5 > \alpha \geq 6.0$	$6.0 > \alpha \geq 2.5$	$2.5 > \alpha \geq 1.3$	$1.3 > \alpha$

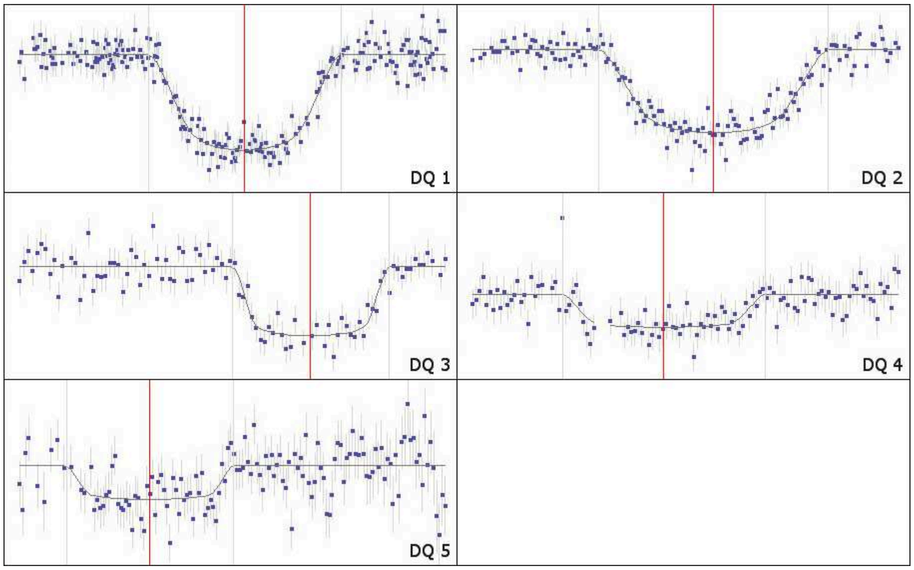

Fig. 3. Examples of the light curve with the different DQ index.

The number α is further transformed for better lucidity to the scale from 1 to 5 where 1 presents the best quality data and the value 5 the worst data (Tab. 3, Fig. 3). These thresholds are used only if whole transit is observed or when we take over whole light curve (AXA, TRESCA). If some part (egress or ingress) is missing in the dataset, the observation automatically gets the worst DQ index and in the notice column in the summary table the notice "*Only partial transit*" is generated. When we take over only the results of midtransit time, transit depth and length of the transit (not the whole light curve) we usually give the DQ equal 1.

3.3.1 How to download data

In the O-C plots section of the ETD you can also download the data for your further studies. If there is displayed whole light curve you can download it using link in the DQ column. Whole table including the O-C residuals can be downloaded directly using link "*Show data as ASCII table separated by semicolon*" below the table. If the transit observation that you used in your next study was captured to ETD from literature, you can find reference in column "Author & REFERENCE", so the source paper should be cited in common way. If transit observation was published in some on-line source

(AXA, TRESCA), ask observers for a permission and other useful comments about the data. We can supply you with e-mail contact to observer if necessary.

4 Future development and discussion

We have created the on-line portal to supply observers with information like transit predictions, TTV, variation of depth and duration plots with availability to draw user observation to the plot. We think that main part of the database is now ready to use and should be useful tool for community.

In future we plan some improvements of the database to be more user-friendly. We also plan to implement limb darkening tables into our fits. Further in the future we would like to develop a (semi)automatic procedure for searching of the transit timing variations in the O-C diagrams.

5 Acknowledgments

The Exoplanet Transit Database is maintained by the Czech Astronomical Society (CAS), an almost 100 years old astronomical society with hundreds of members - professional and amateur astronomers in the Czech Republic. ETD is stored on the web server of CAS which is periodically backup. The server and CAS itself are supported by grants by Czech national Council of Scientific societies and membership fees. The long history of our organization, large membership platform and financially assured operation of the server are the basic conditions making the ETD permanent source where observers can store their data securely. This investigation was supported by the Grant Agency of the Czech Republic, grant No. 205/08/H005. We also acknowledge the support from the Research Program MSM0021620860 of the Ministry of Education.

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